Renewable and Sustainable Energy Reviews 35 (2014) 436–444

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Modeling of biomass potential from agricultural land for energy utilization using high resolution spatial data with regard to food security scenarios

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ARTICLE INFO

Article history:
Received 21 December 2012
Received in revised form
14 March 2014
Accepted 6 April 2014
Available online 7 May 2014

Keywords:
Agricultural land
Biomass potential
Energy crops
GIS
Modeling
Residual biomass

ABSTRACT

The paper presents results of modeling biomass potential under different scenarios of agricultural land utilization, which represent strategies of national food security. High resolution spatial data (GIS) including valuation of agricultural land, maps of actual utilization of agricultural land, yields of annual food crops and yield curves of perennial energy crops derived from empirical field data were used. The biomass sources used were residual straw from conventional agriculture crops (cereals, rape) and lignocellulose biomass from perennial energy crops (poplar, willow, Miscanthus, reed canary grass, hybrid sorrel, and other grasses). Biomass potential is modeled using original methods and algorithms that enabled the respecting of several its limitations (nature and soil protection, competition of crops for land, and use of straw for animal production). For the actual modeling—calculating the biomass potential for a given territory—a geographic information system is used (software TopoL©). Results of analyses confirmed that residual of biomass has good potential as source of energy in the Czech Republic (about 121 PJ/year which equals to 6.8% of primary energy sources used in 2012), though the total number is lower than in previous assessments. The current biomass potential can be significantly increased with allocation of energy crops on less fertile land according to food security scenarios. Modeling also showed that biomass potential is non-linearly dependent on land allocated for energy crops. Soil and climate conditions of agricultural land allocated (available) for biomass production and its suitability for new energy crops play the decisive role in the definition of future biomass potential from agriculture land. Practical outputs of the modeling are yield maps of individual and mixed biomass sources as well as databases of biomass potential under different food security scenarios for regions of the Czech Republic, which can be used for planning of sustainable development of bioenergy.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.04.008
1364-0321/

1. Introduction

In Directive 2009/28/EC, the European Union set out goals to use renewable energy sources for the year 2020 in the form of the required proportion of RES in covering the final energy consumption. The goal is set both for the EU as a whole and for the individual EU member states. According to Directive 2009/28/EC, the individual member states were obliged to prepare a National Renewable National Action Plan (NREAP) [1], which documents the initial situation (2010) and the method of achieving the (binding) goals in 2020. The highest share in final energy consumption in 2010 for EU as a whole belongs to heating and cooling (48%), followed by electricity consumption (25%) and consumption in transport (27%), assuming that the structure of final energy consumption will remain the same until 2020.

Renewable energy sources currently (2010) contribute about 11.5% of the final energy consumption in the EU and the EU target by 2020 (see Directive 2009/28/EC) requires increasing this to 20%. In the Czech Republic, the share of RES in the final energy consumption is presently (2010) at about 8.4%, and NREAP expects it to rise to 13.5% (2020) [1].

Biomass is currently the most important renewable energy source (RES) in the context of both the Czech Republic and the EU as a whole. Biomass had a 90.9% share in 2010 in the EU RES total contribution in the final energy consumption for heating and cooling and it is expected that a high share of biomass will be retained despite the anticipated rapid development of other renewable energy sources (an increase of other RES about 243% between 2010 and 2020) [1]. According to the NREAPs of the individual EU countries it can be expected that the share of biomass in the final energy consumption from RES for heating and cooling in 2020 will reach about 81%, which means an increase in the amount of biomass in absolute terms by about 46%. According to the NREAPs, in the next decade biomass will remain an important RES in the electricity production in the EU as a whole. In 2010, 17.6% of RES used for production of electricity came from biomass (in all its forms—solid biomass, biogas, and liquid biofuels) and by 2020 this should increase to19.1%. This means 1.87 times increase of power generation using RES and 2.03 times increase of biomass use for electricity production (in absolute values).

The Czech Republic is currently characterized with the high share of solid fuels (namely low quality domestic brown coal) both in the structure of primary energy used (2012 figures: 41% solid fuels including solid biomass, 20.4% liquid fuels, 15.9% gaseous fuels including biogas, 18.5% nuclear, and total RES contribution is 7.8% of total primary energy sources) and in the portfolio of gross power generation (47.3% solid fuels including solid biomass, 34.6% nuclear, 5% gas, 3.4% hydro, and 2.5% PV) [2]. In 2012 RES contributed 8.1 TWh, which is 11.4% of the total inland gross power consumption. Solid biomass currently (2012) contributes 63% to the total RES contribution to primary energy sources [3]. Total utilization of solid biomass was 1.458 mt for power generation and 2.047 mt for heat production in 2012 [3]. Solid (wood) biomass namely in the form of residuals from the wood processing industry and forestry currently plays the most important role (2.7 mt of total 3.5 mt).

Similarly as in the EU, biomass plays an important role in the Czech Republic's energy strategies. In 2010 biomass covered 97% of RES in the final energy consumption for heating and cooling, and the NREAP expects the Czech Republic to maintain this high percentage until 2020. In the Czech Republic (2012) biomass has a 40% share in the total share of RES in gross electricity generation, which according to the NREAP is expected to increase to 53% by 2020, i.e., the production of electricity from renewable energy sources is expected to grow from 8.06 TWh to 11.7 TWh between the years 2012 and 2020.

The EU (e.g., in Energy Road Map 2050 [4]) and Czech Republic (e.g., in State Energy Policy 2012–2040 [5]) documents, dealing with the time period after 2020 count with a further massive increase in the share of RES, where biomass will continue to play a key role in the overall contribution of RES. Such a rapid increase in the expected use of biomass cannot be secured without the use of large areas of agricultural land for the cultivation of biomass for energy purposes. The reason is that the sources of waste and residual biomass to be used for energy purposes have already been largely exhausted. Formulating an effective strategy to meet the defined RES-use goals including using biomass as the main type of RES, requires, inter-alia, determination of the biomass potential in relation to how the agricultural land is used. The key aspect here is how much of agricultural land will be available for targeted cultivation of biomass for energy purposes. This question must be dealt with not only by the Czech Republic, but by all the EU member states.

The development of growing biomass for energy purposes on agricultural land is still in its initial phase. In the last decade, especially classical agricultural crops were grown for the production of liquid biofuels (rapeseed for producing biodiesel, corn and sugar beet for bioethanol production), as input to the biogas plants (maize for green mass). In particular, the support for the production of liquid biofuels has often been criticized in recent years as one of the factors leading to a sharp rise in agricultural commodities between 2004 and 2008 [6,7,8,9]. Many analysts argued that both political targets and economic support of biofuels development (resulting in the massive subsidizing of biofuels production) were one of the crucial factors causing this rise [10,11]. The development of the use of biomass for energy purposes is thus to be understood in direct relation to the food production, and the objectives in the use of biomass should be measured with regard to the potential of biomass corresponding to the area of land that is potentially available for the cultivation of energy crops (while maintaining the required level of food production).

This paper presents a methodology for determining the potential of biomass based on combining information from evaluating soil and climatic conditions of the land with the energy crop yield curves under the conditions of the particular land. When applying the methodology, i.e., calculating the biomass potential for a given territory, geographic information systems are used. This methodology, as is further presented in the paper, enables the user to respect a number of limitations in determining the potential (for example, excluding certain lands from cultivation of biomass for energy purposes, assigning a given crop to the land with an optimum energy yield for the respective climatic and soil

conditions of the land, respecting the economic aspect of the biomass production cost demands, etc.). The methodology also enables the determination of the scope of the biomass potential according to the allocated area of agricultural land for energy crop growing and in setting the curve of dependence of the biomass potential on the allocated area of agricultural land, respecting the nonlinearity of the dependence.

The methodology also enables defining the task in the reverse order, i.e. to find a portion of agriculture land, which should be assigned for the energy crop to obtain required biomass potential. The methodology described here is applicable in countries that have information on the soil and climate characteristics of the land, and test results for energy crops under different climatic and soil conditions. This information is available for instance in the Slovak Republic and Germany, with less details being available for instance in Spain or England.

2. Materials and methods

2.1. Data sources

Several studies of biomass potential assessments were carried out in the Czech Republic in the last 13 years [12–17]. Their authors had used different approaches and methodologies, which led to different results not only in the total potential, but mainly in the distribution of potential among different biomass sources, time horizons and geographical areas. Forest residues, straw and energy crops have had approximately an equal contribution to the overall biomass potential in earlier studies. The importance of intentionally grown biomass (energy crops) has been confirmed for future development of biomass in all recent studies.

Similar results can be found in analyses made on a European or global level. Berndes et al. [18] reviewed 17 studies on global potential of biomass which could contribute to the future substitution of nonrenewable energy sources. Estimated range of global biomass potential is from below 100 EJ yr^{-1} to more than 400 EJ yr^{-1} in the year 2050. The authors of this comparative study conclude that such a huge range in global biomass potential estimation is caused by the uncertainty associated with the two key factors influencing global biomass potential— assumptions on land availability and yield levels of intentionally planted energy crop. Widely different opinions and used assumptions adopted by the individual authors play also very significant role.

Thrän et al. [19] studied 19 different global biomass assessments that identified the biomass potential from energy crop between 0 EJ yr^{-1} and 1272 EJ yr^{-1} in 2050. Business as usual biomass potential in energy crop is expected to grow from 27 EJ (2010) to 96 EJ in 2050. Introduction of different limitations and barriers leads to significant reduction of biomass potential from energy crop—e.g. sustainable land use scenario leads to the significantly reduced and almost constant contribution from energy crop to the global biomass potential (18 EJ in 2010 and 16 EJ in 2050).

Erb et al. [20], using the biophysical biomass-balance model, determined the global bioenergy potential (as the contribution to the primary energy sources) as 77 EJ yr^{-1}. They highlighted biodiversity conservation policies, creation of the good conditions for the investors to secure their investments including the political stability, changes in food market and in the effectiveness of the agriculture production including the crop yields and, last but not least the avoidance of long carbon payback time from the deforestation as the key factors influencing the future role of energy crop and its contribution to the total global biomass potential. When applying the different scenarios of the food market future development authors determined the range of future global energy crop potential from 26 to 141 EJ yr^{-1}. Exclusion of areas, which were left for biodiversity protection on global level and also land in countries with high risk for the investors (thanks to the political, economic instability, etc.) further, according to the authors, reduces energy crop potential by up to 45%.

In the most recent overview of bioenergy potentials Batidzirai et al. [21] conclude that results of different studies on (global) biomass potential vary significantly. Main reasons of biomass potential variations are different methodologies and assumptions applied and the different set of data used for the biomass potential assessment. Authors argue that many of these studies do not work with spatial detail on land availability and suitability. They highlighted different ways of competition for water resources inclusion and by the derivation of energy yields using only the crude zoning criteria. Authors recommend, when doing the assessment of future energy crop potential, to use integrated analytical framework working with the all key parameters influencing the biomass potential including high resolution geo-referenced data sets.

One can conclude, based on literature search following: 1) the definition of the type of biomass potential and especially its barriers and limits for biomass utilization is also applied differently in these studies. Most studies assess the realizable biomass potential, but they differ quite much in the definition of its barriers (especially technical, and environmental). Most studies also do not consider more scenarios of biomass development. 2) The applied methodologies often are not described in the published reports, which make the comparison and validation of the results quite difficult. Some assessments used only the statistical data of biomass production, land availability and yields of (energy) crops to calculate the biomass potential using simple formulas and indices.

Until recently only one study in the Czech Republic [13] used GIS (digital maps and databases) to analyze biomass potential, and then using only very general data sources such as publicly available atlases. At present new very detailed GIS sources are available, such as forest management plans, agricultural land valuation and nature protection maps on the national level. The presented methodology of biomass potential assessment combines these new GIS sources with the statistical data and results of research on the biomass productivity of new energy crops (poplar, willow, Miscanthus, etc.) from many sites with different climatic and soil conditions [22–24]. The dynamic character of the presented methodology, which enables the creation of variants of future biomass availability development from agricultural land with regard to food security scenarios and the calculation of needed agriculture land for the required biomass potential, is one of its the important features and advantages.

Tan et al. [25] used the GIS analysis technique with a land evaluation called Agro-Ecological Zoning (AEZ) and a simulation model developed by FAO for calculating maximum potential of biomass and grain yield of wheat. It divides global area of land into smaller grids, and calculates crop potential productivity by taking account the crop characteristics, the climatic factors of radiation and temperatures in growth periods together with the actual photosynthesis capacity of wheat. Hoogwijk et al. [26] analyzed geographical potential of biomass that could be produced from abandoned agricultural and low-productivity lands globally and in long term scenarios (2050–2100) using the integrated GIS based model. They identified areas with high potential for future development of energy crops under four IPCC SRES land-use scenarios. They could not include economic, social or political factors, but they stressed importance of food security and biodiversity preservation in these areas and lands.

2.1.1. Agricultural land (sites) valuation

The presented methodology is based on assigning biomass yields of individual energy crops to the individual valuated soil-ecological

units (VSEU or BPEJ in Czech) of Czech agricultural soil valuation. The valuation has been established based on the evaluation of the Czech Agricultural Land Fund in the years 1973–1978 with the use of a comprehensive soil survey [27,28]. The valuated soil-ecological units are expressed in a five-digit numerical code (written as, e.g., 2.11.14). The first digit indicates the climatic region (CR), the second and third digits indicate the main soil unit (MSU), the fourth digit determines the combination of slope and exposure of the land to the cardinal points, and the fifth digit determines the combination of depth of the soil profile and its skeleton. Climatic regions include areas with approximately identical climatic conditions for growth and development of agricultural crops and they differ primarily in terms of the amount of average daily air temperature above 10 °C, the average annual air temperature, the average annual rainfall, the probability of dry growing seasons, and the moisture confidence. Ten climatic regions and 78 main soil units, which are characterized by soil type, subtype, soil matrix and the degree of hydromorphism, have been defined in the Czech Republic. Climatic region and main soil unit form over 550 so-called main soil and climate units (MSCU), which were used in the methodology as main characteristic of agricultural land quality. For these units an expected yield of main products (e.g. grain, rape seed, and hay) is available for the most conventional crops [29,27,28].

2.1.2. Typology of agricultural sites (land suitability types) for energy crops

A key step in the methodology was the development of a typology of agricultural sites for cultivation of perennial energy crops, which divides land into land suitability types for each crop and also gives the expected yield of biomass in these categories. Two resources were used to create the typology: biomass yields of energy crops in experimental and commercial plantations measured under the research projects [22–24,29] and the units of the Czech agricultural soil valuation (VSEUs or MSCU described previously).

By using empirical yield data from energy crop plantations, we made an expert estimate of the suitability of each CR (climatic region) and MSU (main soil unit) for the cultivation of energy crops by assigning weights to their values. The missing data were gradually supplemented by an expert review in collaboration with leading specialists on particular energy crops and soil valuation. The rate of suitability of each MSCU was subsequently determined by intersecting the CR × MSU weights into 5 categories (land suitability types) as according to the suitability for the cultivation of each energy crop.

2.1.3. Yields of different crops

Expected yields of conventional crops (annual crops for food production) were calculated as average yields from statistical yearbooks for three categories of land suitability types related to units of Czech agricultural soil valuation (MSCU).

For lignocellulose perennial energy crops yield curves related to categories of type of agricultural land (land suitability types) have been created. The curves show dynamics and quantity of harvestable biomass during the life span of energy crops plantations. Experimental plantations of selected energy crops (poplar, willow, Miscanthus, reed canary grass, etc.), established by the Silva Tarouca Research Institute for Landscape and Ornamental Gardening and the Crop Research Institute, were primarily used for collecting input data to define the typical yield curves. These plantations were established to test clones and cultivars of energy crops for biomass production under the different climatic and soil conditions of the Czech Republic.

2.1.4. Assessment of residual biomass (straw, grass) from conventional agricultural crops

The amount of straw produced from conventional agriculture (from the cultivation of crops such as wheat, rapeseed, rye, barley, etc.) is linked to the grain yield per hectare. The potential of residual straw from cereals and oilseed rape is calculated by multiplying the yield by a coefficient (*K*s) of grain/straw ratio and by calorific value; see Table 1, e.g., for wheat the coefficient is 0.8; thus the weight of straw is 80% of grain weight [29] and energy content is obtained by multiplying straw weight by the calorific value. Straw used for soil improvement is included in these coefficients, which is typically about 30% of aboveground biomass. Energy content in straw is calculated by taking 12% straw moisture at harvest. However, the usable potential of cereal straw for energy purposes is lower—it is necessary to deduct straw used for animal production (cattle, sheep, rams, and horses). Data on number of farm animals were obtained from the Czech Statistical Office and were processed using an evaluation methodology developed for agricultural enterprises, under which the cattle consumption is 1.5 kg of straw per head per day for litter and 1 kg for feed. One sheep consumes 1 kg of straw per head per day for litter and 1 kg for feed. The currently applied plowing of some straw to enrich soil with organic matter and to increase the humus

Table 1
Expected yield ranges in land suitability types and other parameters of selected conventional crops used in the Czech Republic case study.
Source of data [27–29].

Order of crops according to site requirements	Crops	Yield range in land suitability types (t ha^{-1})	Straw coefficient (straw/grain ratio)	Calorific value (12% moisture content) (GJ t^{-1})
1	Sugar beet	29.50–36.40	–	–
		36.41–43.31		
		43.32–50.22		
2	Corn for seed	0–2.44	–	–
		2.45–4.89		
		4.90–7.34		
3	Spring barley	2.16–2.95	0.7	15.7
		2.96–3.75		
		3.76–4.55		
4	Winter wheat	2.85–3.80	0.8	15.7
		3.81–4.76		
		4.77–5.72		
5	Rape	1.26–1.79	0.8	17.5
		1.80–2.33		
		2.34–2.88		
6	Corn for silage	28.96–34.62	–	–
		34.63–40.29		
		40.30–45.96		
7	Triticale	7.41–10.57	1.3	15.7
		10.58–13.74		
		13.75–16.90		
8	Other forage crops	5.70–8.13	–	–
		8.14–10.57		
		10.58–13.00		
9	Rye	4.26–4.83	1.2	15.7
		4.84–5.39		
		5.40–5.95		
10	Oat	3.48–4.07	1.05	15.7
		4.08–4.68		
		4.69–5.29		
11	Other crops according to yield of wheat	3.56–4.75	–	–
		4.76–5.95		
		5.96–7.15		

Methodology of calculation: VÚKOZ, v. v. i.

content is significant only for heavier soil; otherwise it has an effect only while spreading liquid manure or other nitrogen fertilizer. In the case of rape, all the residual straw can be utilized for energy purposes. Technological losses during harvest and transport (up to 10%) shall be also taken into account. The last step requires that the residual straw after deducting the consumption of livestock production be multiplied by the calorific value (at 12% humidity) for a single crop (Table 1) [29].

The biomass potential from permanent grasslands (PGL), which can be utilized as the input to the biogas stations, is the sum of grass yields from individual field blocks registered as PGL. These tabular yields defined from statistical evidence for each main soil and climate unit (MSCU), contain a “raw” yield per 1 ha (80% moisture content), so they must be corrected to the yield with 65% moisture. 1 t of grass from PGL with 35% dry matter content produces about 175 m^3 of biogas, which means an energy potential of 3.3 GJ [29].

The calculation of energy potential of silage maize for biogas is based on tabular yields defined for MSCU from statistical evidence. 1 t of silage at 35% of dry mass produces about 240 m^3 of biogas, which means an energy potential of 4.5 GJ t^{-1} [29].

2.1.5. Energy crop considered in models

The methodology and developed model consider the following new lignocellulose energy crops on arable land: short rotation coppices of fast-growing trees, non-woody energy crop stands and triticale. Short rotation coppices (SRC) are planted with the most suitable clones and varieties of poplars or willows under the Czech conditions. The basic characteristics of these plantations include a 20–25-yr plantation life cycle, rotation period of 3–5 yr, and a gradual increase in biomass yields from time of establishment with the production optimum being reached between the 8th and 12th year. The plantations are established using cuttings planted by a planting machine, and harvested using a special machine (usually a corn harvester adapted for this purpose) that directly produces wood chips [22].

Non-woody energy crops are grasses and perennials, e.g., hybrid sorrel (Schavnat), Miscanthus (*M. giganteus*), cocksfoot, tall cat grass, reed canary grass, and Hungarian brome. All of these crops differ from food crops in that they are produced for lignocellulose biomass and not for nutritional value. The main advantage of these crops is that they can be harvested using the standard harvesters.

Yield categories of different kinds of energy crop were created according to the results of testing of these crops in the research plots located in the Czech Republic [22,29,30]; see Table 2. Energy content is calculated by multiplying the yield (in *t*(FM)) by the corresponding calorific value (taking into account the typical moisture content at time of harvest). Calorific values represent typical (average) values obtained during research projects aimed at testing individual kinds of energy crop under soil and climate conditions of the Czech Republic.

Cereal crops grown for energy purposes are advantageous in that biomass can be produced without large capital investments needed for establishment of plantations and harvesting technologies. A typical annual crop considered as an energy crop is triticale. Triticale is a cross between rye and wheat with good yields even under less suitable conditions. It is an undemanding cover crop that tolerates soils with pH unsuitable for other crops and is disease and pest resistant.

2.1.6. Utilization of agricultural land

The commodity surveys and statistical year books and the GIS database (maps) of Land Parcel Identification System (LPIS) were used to identify the actual growing area of main crops on agricultural land in the Czech Republic. The basic unit of registration is a farming block, which represents a continuous area of agricultural land (> 1 ha) used by one farmer. The mapping scale is 1:10,000 of used maps.

2.2. Methodology

The total biomass potential on agricultural land consists of the following:

- Potential of residual biomass from conventional agriculture—primarily unused portion of straw.
- Potential of biomass from energy crop planted on arable land.
- Potential of biomass from permanent grasslands (grass and hay).
- Potential of biomass from SRC plantations established on selected permanent grasslands (utilization of grasslands for conventional agriculture is not assumed due to the environmental restrictions).

The algorithm for calculating actual (current) biomass potential is based on the allocation of individual conventional and energy crops on specific farming blocks. These blocks differ in their soil and climatic characteristics (MSCU) and thus also in expected yield for each crop. The methodology of the algorithm assumes that energy crops always utilize the agricultural land that is considered the lowest quality for conventional crops. The described mechanism of allocating agricultural land for cultivation of energy crops minimizes the potential conflicts of using agricultural land for energy purposes and food production.

The same methodology (i.e., assignment of biomass yields for given kind of crop according to the MSCU) is used to evaluate future biomass potentials on arable land and permanent grasslands. Future planting areas of all energy crops on arable land are

Table 2
Yield ranges of perennial energy crops for their land suitability types and calorific values of their biomass used in the Czech Republic case study. Source of data [29].

Land suitability types	Miscanthus [t(dm) ha^{-1}]	Hybrid sorrel [t(dm) ha^{-1}]	Reed canary grass [t(dm) ha^{-1}]	Poplar and willow SRC [t(dm) ha^{-1}]	Hungarian brome [t(dm) ha^{-1}]	Cocksfoot [t(dm) ha^{-1}]	Tall oat grass [t(dm) ha^{-1}]
	biomass for combustion				**biomass for biogas**		
K1	< 5.0	< 2.5	< 5.0	< 4.5	< 5.0	< 5.0	< 5.0
K2	5.1–9.0	2.6–5.0	5.1–7.0	4.51–6.50	5.1–7.0	5.1–7.0	5.1–7.0
K3	9.1–13.0	5.1–7.5	7.1–9.0	6.51–8.50	7.1–9.0	7.1–9.0	7.1–9.0
K4	> 13.1	7.6–10.0	9.1–11.0	8.51–11.00	> 9.1	9.1–11.0	9.1–11.0
K5	–	> 10.1	> 11.1	> 11.01	–	> 11.1	> 11.1
Moisture contend at harvest (%)	20	20	20	52.5	65	65	65
Calorific value (GJ/t)	13.75	13.76	12.48	7.14	9.43	9.43	9.44

dm = dry matter.

defined by energy and agriculture policy goals. Short rotation coppices are also expected to be grown on permanent grasslands.

The potential of residual biomass from conventional agriculture depends on the structure of conventional crops and the development or decreasing of livestock production. Due to the absence of data on the possible future structure of conventional crops, or the development of livestock production, the determination of residual biomass potential is based on the current structure of conventional crops and condition of livestock production. It is clear that a fundamental change in the structure of conventional crops and in particular a fundamental change in the scope of livestock production would have to bring about an update in the calculation algorithm and adjustment of the biomass potential.

Steps of biomass potential calculation are as follows (see also scheme of modeling—Fig. 1):

1. Identification of the region for which biomass potential is being calculated.
2. Preparation of the general data inputs into the GIS model, i.e.,
   - Identification of shares of conventional crop on arable land in given region.
   - Assignment of MSCU to each registered parcel (plot) of agriculture land (see above).
   - Definition of grain yields for each conventional (food/technical) crop on each MSCU.
   - Definition of biomass yields for permanent grasslands based on MSCU.
   - Definition of biomass yields for each energy crop on each MSCU.
   - Definition of straw to grain yield coefficients for each conventional crop.
3. Definition of the share of arable land used for energy crop.
4. Definition of the share of permanent grasslands used for energy crop (SRC plantations in our study).
5. Allocation of conventional crop to the individual plots (farming blocks) so that the total acreage for each kind of conventional crop would be reached (statistics gives the shares of individual conventional crop in the region without direct link to the individual farming blocks). Allocation of conventional crop is based on the following rules:
   - Individual conventional crops are ordered according to their demand for quality of stand conditions (defined in MSCU by the soil and climate conditions).
   - Conventional crops are allocated to individual plots in the order depending on their requirements for soil quality (see Table 1). Given kind of crop is allocated to land plots with the highest biomass yields until the total growing area in the region is reached.
   - Allocation continues with the kind of crop which is next in order; already occupied plots are excluded from the allocation.
   - Allocation finishes when all farming blocks in the given region are occupied with conventional crops.
6. Allocation of individual energy crop to the individual plots (farming blocks) is according to the following rules:
   - Total future acreage of energy crop is equal to the multiplication of total acreage of arable land and the relative share of the energy crop intended in the given region.
   - Plots of arable land with the lowest yields for the conventional crops are allocated first.
   - To the given plot, the energy crop with the highest biomass yield is assigned (according to biomass yield curves assigned to the MSCUs).
   - The allocation continues until energy crops reach acreage intended for energy production purposes.
7. Allocation of SRC plantations to the individual plots of permanent grasslands is according to the following rules:
   - Total acreage of plots with SRC plantations is equal to the total acreage of permanent grassland in given region multiplied by the relative share of the SRC plantations intended in the given region.
   - Plots with the highest biomass yields from SRC plantations are allocated first.
   - Plots with the specific conditions (e.g., plots in natural parks and other areas with the specific environmental protection are excluded from the allocation).
8. Calculation of potential of the residual biomass (straw) from conventional agriculture taking into account other types of straw utilization. The residual biomass potential in the given region is thus calculated as the sum of grain yields on individual

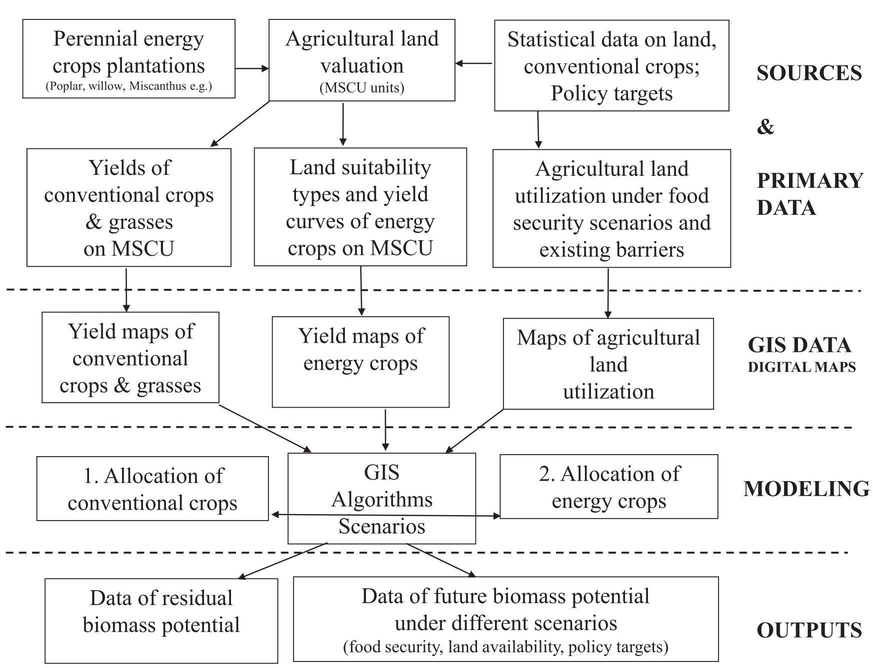

Fig. 1. Scheme of the methodology for modeling biomass potential on agricultural land used in the case study.

plots, multiplied by the straw/grain coefficient. The straw potential is then reduced by the value of straw used for soil improvement and for farm animals (according to the statistics data on number of farm animals in the given region). Energy potential is then calculated using corresponding calorific value for biomass of the given kind of crop (see Table 1).
9. Future potential of intentionally produced biomass from energy crop is calculated as the sum of biomass yields on farming blocks (with MSCUs) of arable land and permanent grasslands allocated for individual kinds of energy crop in the given region (according to described methodology). Energy potential of intentionally produced biomass is calculated using calorific value for the given kind of crop (see Table 2).
10. Calculation of biomass potential from permanent grasslands according to the MSCU of farming blocks.
11. The total biomass potential is equal to the sum of contribution from residual and intentionally grown biomass from arable land and from permanent grasslands.

This algorithm correctly reflects the fact that the increase of land allocation for energy purposes reduces land area for conventional agriculture and thus also the contribution of residual biomass to the total biomass potential. The algorithm can also calculate the biomass potential not only for the given portion of agriculture land allocated to the energy crop, but can be also used to calculate needed area of agriculture land allocated for the energy crop to get required biomass potential. The required biomass potential here is thus the input value for the calculation and portion of agriculture land that should be assigned for the energy crop is the resulting quantity.

3. Results

To calculate biomass potential in the Czech Republic, scenarios were used assuming increasing shares of arable land including the Set Aside Land for the cultivation of energy crops in the range from 0% to 30% (in increments of 5%). In addition the use of 2% of permanent grasslands was assumed for SRC plantations. The highest allocation of farmed land (30+2%) equals to 100% food security scenario defined in the Biomass Action Plan of the Czech Ministry of Agriculture (2012) [31].

The calculation algorithm works by reducing the potential of residual biomass from 0% to 30% of arable land and 2% of the PGL area, which were used for intentional production of biomass. Then the potential of residual biomass is increased by the potential of energy crops grown on 5–30% of arable land and 2% of the PGL. Cultivation of energy crops leads to the higher production of biomass, used either for direct combustion or for biogas production. Results of modeling are presented in Table 3 of all scenarios and biomass sources.

Allocation of less fertile arable land for food crops for cultivation of energy crops leads to an increase in the biomass potential, because large proportion of these soils are very often hydromorphic (with a higher ground water level), which are very suitable for the cultivation of poplar and willow SRC, which often reach their best yields there. Other energy crops also often achieve higher biomass yields than the conventional crops on “less fertile” soil made available for them by the methodology as well as in farming practice.

4. Discussion

Biomass potential from agricultural land for a given area cannot be described by a simple (e.g., one-parameter) dependence between the area of agricultural land for cultivation of biomass for energy purposes and the amount of biomass potential, expressed in energy units (e.g., in PJ). If we assume the application of proper farming practices (e.g., choice of seed and farming practices appropriate to the locality, including fertilization), the biomass yield from the cultivation of energy crops will depend primarily on the long-term climatic and soil conditions of the site. In determining the biomass potential for larger regions (e.g., at the EU NUTS-3 level) or whole countries, it is necessary to respect the great diversity in the climate and soil characteristics. Similar conclusion and recommendation for modeling of future development of biomass potential were drawn by Batidzirai et al. [21].

In addition it is impossible to assume mechanically the cultivation of only selected species of energy crops and it is always necessary to consider the entire portfolio of energy crops. This is both because of the suitability of different crops for the conditions of the site, and also because of the nature conservation and protection of biodiversity. With the “release” of agricultural land for energy purposes it is thus necessary to respect the properties of plots for these purposes. Allocation of certain land for the cultivation of energy crops also means that the plot cannot be used for conventional agriculture and thus it is necessary to reduce the potential in the residual biomass as well (typically the grain straw). The total biomass potential from agricultural land is then given by the sum of residual biomass from the classic agricultural production (straw), intentionally grown biomass on agricultural

Table 3
Biomass potential on agricultural land in the Czech Republic for 0–30% scenarios of agriculture land allocation for energy crops.

Agriculture land allocated for energy crops (%)		0	5	10	15	20	25	30
For combustion								
Residual grain straw	in PJ	79.402	74.544	69.714	64.871	60.003	55.119	50.217
Rape	in PJ	10.854	10.339	9.828	9.308	8.789	8.268	7.744
SRC on arable land and grasslands	in PJ	0	5.994	8.717	11.467	14.311	17.071	19.808
Miscanthus, Schavnat, reed canary grass	in PJ	0	8.159	14.842	21.607	28.524	35.532	42.471
Total (combustion)	**in PJ**	**90.256**	**99.037**	**103.099**	**107.253**	**111.627**	**115.991**	**120.241**
For biogas								
Corn for silage	in PJ	35.095	33.369	31.657	29.931	28.218	26.477	24.750
Permanent grassland	in PJ	32.173	31.250	31.250	31.250	31.250	31.250	31.250
Cocksfoot, tall oat grass, Hungarian brome	in PJ	0	4.656	8.425	12.412	16.414	20.463	24.584
Consumption of livestock production	in PJ	−36.487	−36.487	−36.487	−36.487	−36.487	−36.487	−36.487
Total (biogas)	**in PJ**	**30.781**	**32.788**	**34.844**	**37.105**	**39.394**	**41.703**	**44.096**
Total (combustion+biogas)	**in PJ**	**121.037**	**131.825**	**137.943**	**144.358**	**151.021**	**157.694**	**164.337**

Note: The total area of agricultural land in the Czech Republic is 4.229 mha of which 3.384 is farmed; 2.513 mha is farmed arable land and 0.989 mha is PGL (state to 31.12.2011). Source: Czech Statistical Office.
Note 2: Figures should be interpreted as the contribution of biomass to primary energy sources, i.e., they do not include efficiencies and losses in energy chains to the final consumers.

soil and grass from PGL. The dependence of the total potential of biomass on the area of agricultural land in the Czech Republic states is shown in Fig. 2. The effect of the increased area allocated for energy purposes on the energy potential of residual straw and of energy crops intended for direct combustion is shown in Fig. 3. It is evident that the increase of biomass potential is not directly proportional to agricultural land allocated for energy crops which is caused by different climate and soil requirements and yields of energy crops on allocated ("released") land, e.g. poplar and willow on water logged sites and in colder climatic regions. Thrän et al. [19] found constant contribution relation between land allocated for energy production and biomass potential in their sustainable land use scenario, which is similar to our approach.

The actual biomass production on agricultural land (ignoring the fluctuations given by the particular climatic conditions in the given year) of course depends on what specific land and energy crops are used for biomass production. The process of determining the biomass potential, as discussed in the paper, is built on two basic prerequisites. The first prerequisite is the rationality of the behavior of entities farming on agricultural land (use of appropriate energy crops and farming practices under specific conditions of the site). The second prerequisite is the conservative approach based on the effort not to overvalue the biomass potential in relation to the area of land allocated for the cultivation of energy crops. The methodology is based on the fact that only the land least suitable for conventional agriculture is allocated for energy crops. This obviously affects the yield of biomass for energy purposes. A better utilization of land for the cultivation of energy crops would obviously lead to an increased production of biomass for energy purposes but it would also reduce the production of conventional crops. The presented approach can thus be considered as a method to determine the lower estimate of the biomass potential for energy purposes on the specific percentage of agricultural land area for a defined territory (region, country).

Another factor that must be taken into consideration is the development of agro-technical procedures for the cultivation of biomass for energy purposes. The development of cultivation methods of new energy crops will lead to optimization of agro-technical procedures, and thus an increased efficiency of biomass production can be expected. This will then lead to increasing the competitiveness of cultivated biomass at the fuels market and the possibility to use also the less profitable locations. Given all the above factors, the determination of biomass potential is not a static but a dynamic task in time. The potential of biomass shall therefore be periodically updated taking the current status of all these factors into account.

Results of our work show that the proposed methodology for analysis of biomass potential can produce very detailed geographical data about distribution and amount of different biomass sources in landscape down to the NUTS-4 level. The methodology can also be used for calculating and evaluating different scenarios and tasks that respect different land use patterns, preventing land use conflicts with food crops or nature protection. It can also be used for analysis in wide time scale, from analysis of current biomass potential up to a horizon of a few decades. The methodology created is far more detailed and flexible than those used to date for assessing biomass potential in the Czech Republic [12–16,29].

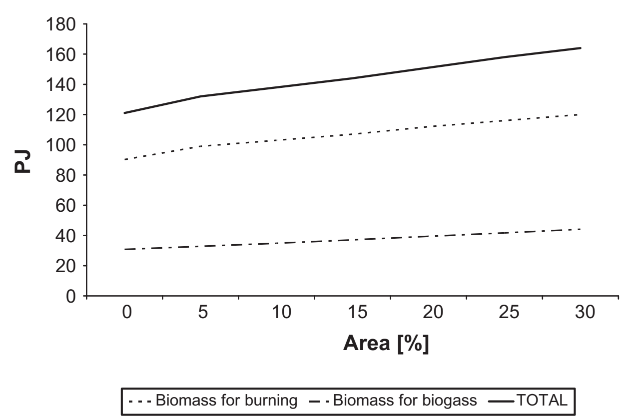

Fig. 2. Total biomass potential (from agriculture land) in the Czech Republic as the function of share of agriculture land allocated for energy purposes.

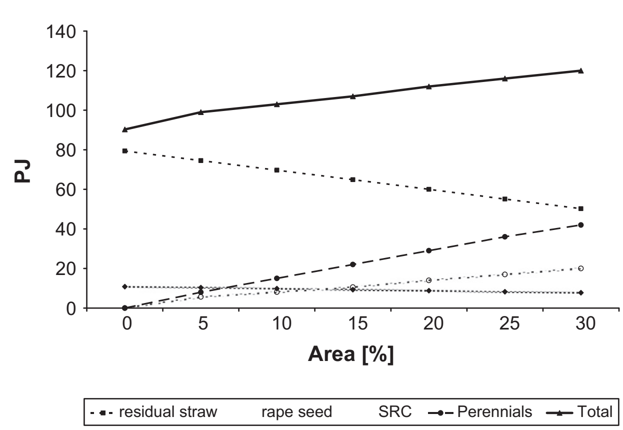

Fig. 3. Potential of individual biomass types (for direct burning) in the Czech Republic as the function of share of agriculture land allocated for energy purposes.

5. Conclusion

In the Czech Republic as in the other EU member states, biomass is recognized as a crucial energy source with the highest growth potential in the future. Information about the potential of biomass often varies depending on the used methodology and data source. The paper presents methodology using high resolution spatial data and GIS tools which can significantly improve accuracy of calculation of current and future potential of biomass in landscape.

Based on carried out analysis of biomass potential with described methodology it is possible to conclude following:

1. Current potential is 121 PJ of biomass suitable for direct burning and biogas production in the Czech Republic which equal to 6.8% of primary energy sources used in 2012. Residual straw from cereals and rape was identified as main source for direct burning (90 PJ). Corn silage and grass from permanent grasslands were used as main sources for biogas (31 PJ). Future biomass potential reached 164 PJ in the case of "100% food security" scenario with 30% of agricultural land allocated for new energy crops.
2. The analysis corrects earlier (more optimistic) assessments, e.g. that from 2008 [16] which calculated that biomass potential would be 194 PJ if 1 mha (29%) of farmed land would be used for production of energy biomass. The main reason for this correction is that the new methodology is using principle that assumes allocation of more productive soil for food production and therefore less productive soil is used for energy crops. The methodology also deducts all residual biomass from land allocated for new energy crops.
3. From results of detailed analysis it is also evident that the increase of biomass potential is not directly proportional to the increase of agricultural land allocated for energy crops especially in case of arable land. Increase of land allocation for

energy crops from 0% to 10% increases total energy potential of biomass by 16.9 PJ and further land allocation from 10% to 20% increases potential by only 13.1 PJ. The reason for this is that stand requirements (climate and soil) of new energy crops are often different from conventional crops. Some of lower-quality soils or less suitable climatic conditions for conventional food crops could be more suitable for new energy crops (e.g. water logged soils or colder climatic regions for poplar and willow).

4. The methodology—based on detailed spatial data and using GIS tools—can significantly contribute to refine the potential of biomass so that the data obtained could serve as a reliable source of information for policy making at national level (e.g., the national energy plan, food security and agricultural policy), as well as for decision making at lower hierarchical levels (region, district, etc.).

Acknowledgments

This study was performed under Project no. VG20102013060, which was supported by the Czech Ministry of the Interior.

References

[1] European Commission. Energy [Internet]. Brussels: National Renewable Energy Action Plans of EU member states; 2009. Renewable energy; [about 2 screens]. Available at: 〈http://ec.europa.eu/energy/renewables/action_plan_en.htm〉 [accessed 13.03.2014].
[2] Energy Regulatory Office. [Internet]. Prague: Annual Data Summary of Electric Power System of the Czech Republic in 2012; 2013. Statistics Unit ERO; [about 31 screens]. Available at: 〈http://www.eru.cz/dias-browse_articles.php?parentId=195〉 [accessed 14.02.2014].
[3] Ministry of the Industry and Trade. [Internet]. Praha: [Renewable Energy Sources in the Czech Republic in 2012]; 2013. Data support department; [about 66 screens]. Available at: 〈http://www.mpo.cz/dokument144453.html Czech〉 [accessed 15.02.2014].
[4] European Commission. [Internet]. Brussels: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; 2011. Energy Roadmap 2050, COM/2011/0885 final [cited Mar 13]; [about 20 screens]. Available at: 〈http://www.ipex.eu/IPEXL-WEB/dossier/document/COM20110885.do〉.
[5] Forejtová V. [Internet]. Government negotiations about state energy policy. 2012 Nov; [2 p.]. Available at: 〈http://www.mpo.cz/dokument108147.html Czech〉 [accessed 12.02.2014].
[6] Henke J, Klepper G, Schmitz N. Tax exemption for biofuels in Germany: is bioethanol really an option for climate policy? Energy J 2005;30:2617–35.
[7] Patzek TW, Anti SM, Campos R, Ha KW, Lee J, Li B, et al. Ethanol from corn: clean renewable fuel for the future, or drain on our resources and pockets? Environ Dev Sustain 2005;7(3):319–36.
[8] Moore A. Biofuels are dead: long live biofuels(?)—Part one New Biotechnol 2008;25(1):6–12.
[9] Rabbinge R. De plant als fabriek van non-food. Change Mag 2008;4:73.
[10] British Broadcasting Corporation. [Internet]. BBC Mundo. Inflación en alimentos limita a la ONU; [updated 2007 Jul 7; [about 1 screens]. Available at: 〈http://news.bbc.co.uk/hi/spanish/specials/2007/clima/newsid_7085000/7085227.stm Spanish〉 [accessed 13.03.2014].
[11] Wroughton L. [Internet]. Update 3-biofuels major driver of food price rise-World Bank Reuters; 2008 Jul 28. Available at: 〈http://uk.reuters.com/article/2008/07/28/worldbank-biofuels-idUKN2861501620080728〉 [accessed 12.03.2014].
[12] Lewandowski I, Weger J, van Hooidonk A, Havlickova K, van Dam J, Faaij A. The potential biomass for energy production in the Czech Republic. Biomass Bioenergy 2006;30:405–21.
[13] Scholes H, Manning M, Markvart T. Czech Republic Renewable Energy Study. Resource Assessment Report. Prague: CSMa, Pernyn MoEnv; 1997.
[14] Sladký V. Research Institute of Agricultural Engineering, p. r. i., Praha, Czech republic. Utilisation of biomass as substitute of fossil fuels. In: Weger J, editor. Production and utilization of biomass as renewable source of biomass in the landscape. Final report. MŽP Čr Praha: VÚOZ Průhonice (CZ); 1996 Nov 22. Project no. PPŽP 640/96.
[15] SRCI CS. National energy efficiency study of the Czech Republic, World Bank, Czech; 1999.
[16] Pačes V, Bubeník J, Dlouhý V, Hrdlička F, Kubín M, Moos P, et al. [Internet]. Report of independent expert commission on review of energy needs of the Czech Republic in long-term horizon. 2008. Available at: 〈http://www.vlada.cz/assets/media-centrum/aktualne/Pracovni-verze-k-oponenture.pdf Czech〉 [accessed 13.03.2014].
[17] Havlíčková K, Suchý J. Development model for energy crop plantations in the Czech Republic for the years 2008–2030. Renew Sustain Energy Rev 2010;14(7):1925–36.
[18] Berndes G, Hoogwijk M, van den Broek R. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 2003;25(1):1–28.
[19] Thrän D, Seidenberger T, Zeddies J, Offermann R. Global biomass potentials—resources, drivers and scenario results. Energy Sustain Dev 2010;14:200–5.
[20] Erb KH, Haberl H, Plutzar C. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. Energy Policy 2012;47:260–9.
[21] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials—methodological lessons from review of state of the art bioenergy potential assessments. Renew Sustain Energy Rev 2012;16:6598–630.
[22] Weger J. Yields of selected willow and poplar clones after 9 years of growing in short rotation coppice. Acta Pruhon 2008;89:5–10 (Czech).
[23] Weger J, Knápek J, Havlíčková K, Vlasák P, Zoning of agricultural land for willow and poplar as a tool to increase biomass production efficiency and to prevent risks of biomass production. In: Proceedings of the 15th European biomass conference and exhibition. Berlin (Germany). Florence: ETA-Renewable Energies; May 7–11, 2007.
[24] Havlíčková K, Knápek J, Vašíček J, Weger J. Biomass as renewable source of energy, economic and energy aspects. Acta Pruhoniciana 2005;79:1–67 (Czech).
[25] Tan G, Shibasaki R, Rajan KS. The study of global land suitability evaluation: case of potential productivity estimation for wheat. In: Proceedings of 19th ISPRS congress, Vol. XXXIII, Part B4 (1–3); Amsterdam (The Netherlands). ISPRS, July 16–23 2000.
[26] Hoogwijk M, Faaij A, Eickhout B, de Vries B, Turkenburg W. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass Bioenergy 2005;29(4):225–57.
[27] Rejfek F, Dolek J, Dušek J, Knobová A, Mužík V, Němec J, et al. Valuation of Czechoslovak agricultural lands and directions of their utilisation, 5. Praha, Czech: Ministry of Agriculture of the Czech Republic; 1990.
[28] Němec J. Valuation and appraisement of agricultural land of the Czech Republic. Praha, Czech: Institute of Agricultural Economics; 2001.
[29] Havlíčková K, Suchý J, Weger J, Šedivá J, Táborová M, Bureš M, et al. Analysis of biomass potential analysis in the Czech Republic. Průhonice (Czech): VÚKOZ; 2010.
[30] Vávrová K, Knápek J. Economic assessment of miscanthus cultivation for energy purposes in the Czech Republic. J Jpn Inst Energy 2012;91:485–94.
[31] Ministry of Agriculture. Biomass Action Plan for period 2012–2020. Prague (Czech): MŽP; 2012.